PULSED CHARGING OF CAPACITOR BANK BY COMPACT EXPLOSIVE-DRIVEN HIGH-VOLTAGE PRIMARY POWER SOURCE BASED ON LONGITUDINAL SHOCK WAVE DEPOLARIZATION OF FERROELECTRIC CERAMICS

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ABSTRACT

Results of the investigation of the operation of autonomous ultracompact explosive-driven high-voltage primary power sources based on longitudinal (when the shock wave propagates along the polarization vector $\mathbf{P}_0$) shock wave depolarization of ferroelectric materials in the open circuit and charging modes are presented. The energy-carrying elements of shock wave ferroelectric generators (FEGs) were poled lead zirconate titanate (PZT) $Pb(Zr_{52}Ti_{48})O_3$ polycrystalline piezoelectric ceramic disks with volume 0.35 cm^3. The PZT modules were shock compressed in the stress range from 1.5 to 3.8 GPa by a longitudinal shock wave generated by high explosives. In the charging mode, the FEGs provided pulsed power with peak amplitudes up to 0.29 MW. The maximum efficiency of the electric charge transfer from the energy-carrying PZT elements to the capacitor bank was 46%.

I. INTRODUCTION

Explosive-driven electrical generators are considered to be the most efficient autonomous compact pulsed power devices. The design and performance of recently developed autonomous pulsed power sources that use the electromagnetic energy stored in ferroelectric materials are described herein [1]. Ultracompact explosive-driven generators are based on longitudinal shock wave depolarization of ferroelectric materials; that is, when the impact-driven shock wave propagates along the polarization vector $\mathbf{P}_0$ of the ferroelectric energy-carrying element. This type of generator is referred as a longitudinal shock wave FEG [1]. The efficiency of the FEG depends on the order of depolarization of the ferroelectric energy-carrying element due to the action of a shock wave. In [2], we experimentally investigated operation of FEGs with resistance loads and the depolarization of the ferroelectric energy-carrying elements within the generator due to the action of a shock wave generated by the detonation of a high explosive (HE) charge. It was shown that longitudinal shock wave compression of a ferroelectric energy-carrying element by pressures in the range 1.5-3.8 GPa caused almost complete depolarization of the sample [2]. In this work we performed a series of experimental investigations of longitudinal shock wave FEGs operating in the open circuit and charging modes, where the load of the generators was a capacitor bank having different capacitances.

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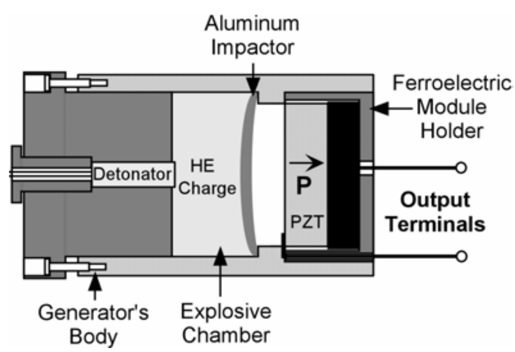

Figure 1. Schematic diagram of an explosive-driven longitudinal shock wave ferroelectric generator.

II. EXPERIMENTAL TECHNIQUE

The schematic diagram of an explosive-driven longitudinal shock wave ferroelectric generator is shown in Fig. 1. It contains a cylindrical body, an explosive chamber, an aluminum impactor (flyer plate), a holder containing the ferroelectric module (the energy-carrying element), and a load circuit. All the generators described in this paper were loaded with 14 g of desensitized RDX and initiated by a single RP-501 detonator. Detailed information about the design of the longitudinal shock wave FEG can be found in [1].

Report Documentation Page			*Form Approved OMB No. 0704-0188*

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 2005	**N/A**	**-**

4. TITLE AND SUBTITLE	
Pulsed Charging Of Capacitor Bank By Compact Explosive-Driven High-Voltage Primary Power Source Based On Longitudinal Shock Wave Depolarization Of Ferroelectric Ceramics	5a. CONTRACT NUMBER
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Loki Incorporated, Rolla, MO 65409, U.S.A.**	8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES

See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. IEEE International Pulsed Power Conference (19th). Held in San Francisco, CA on 16-21 June 2013.

14. ABSTRACT

Results of the investigation of the operation of autonomous ultracompact explosive-driven high-voltage primary power sources based on longitudinal (when the shock wave propagates along the polarization vector P0) shock wave depolarization of ferroelectric materials in the open circuit and charging modes are presented. The energy-carrying elements of shock wave ferroelectric generators (FEGs) were poled lead zirconate titanate (PZT) Pb(Zr52Ti48)O3 polycrystalline piezoelectric ceramic disks with volume 0.35 cm3. The PZT modules were shock compressed in the stress range from 1.5 to 3.8 GPa by a longitudinal shock wave generated by high explosives. In the charging mode, the FEGs provided pulsed power with peak amplitudes up to 0.29 MW. The maximum efficiency of the electric charge transfer from the energy-carrying PZT elements to the capacitor bank was 46%.

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**4**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

The energy-carrying elements in the generators were poled lead zirconate titanate $Pb(Zr_{52}Ti_{48})O_3$ polycrystalline piezoelectric ceramic disks (supplied by EDO Corp.) having diameter D = 26 mm and thickness h = 0.65 mm (volume 0.35 cm^3). The parameters of the $Pb(Zr_{52}Ti_{48})O_3$ are as follows: density 7.5×10^3 kg/m^3, dielectric constant ε = 1300, Curie temperature 320° C, Young's modulus 7.8×10^{10} N/m^2, piezoelectric constant $d_{33} = 295\times10^{-12}$ C/N, and piezoelectric constant $g_{33} = 25\times10^{-3}$ m^2/C.

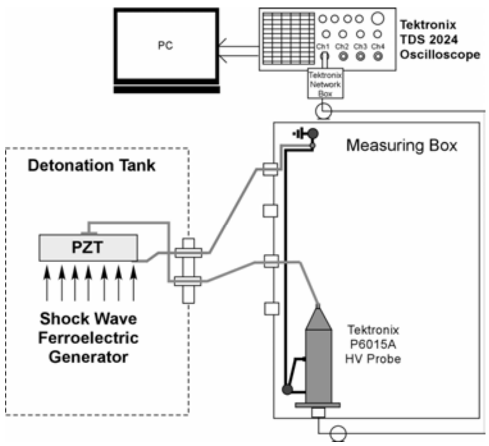

Figure 2. Schematic diagram of the measuring system for investigating the operation of FEGs in the open circuit mode.

All explosive experiments were performed at the Rock Mechanics and Explosive Research Center at the University of Missouri-Rolla, where we developed the experimental setup for testing explosive-driven pulsed power and microwave sources. Generators were placed inside a detonation tank, and all measuring and recording systems were placed outside the tank (Fig. 2). More information about the experimental setup for studying explosive pulsed power systems can be found in [3].

III. EXPERIMENTAL RESULTS

We performed a series of investigations with FEGs operating in the open circuit and charging modes. A schematic diagram of the system for measuring output signals produced by FEGs operating in the open circuit mode is presented in Fig. 2. The generator load was a Tektronix P6015A high-voltage probe (resistance 100 MΩ, 3 pF). The high-voltage output terminal of the FEG (back plate of the PZT disk) was connected directly to the input of the probe. The negative (front) plate of the PZT disk was grounded.

Operation of the FEG is as follows. After detonation of the high explosive charge, the aluminum flyer plate (Fig. 1) is accelerated under the action of a shock wave and high-pressure gases. The collision of the flyer plate with the ferroelectric disk's front plate initiates a shock wave in the ferroelectric body that propagates through the PZT disk and depolarizes it. The depolarization process releases the induced charge on the metallic contact plates of the ferroelectric disk and a pulsed electric potential (electromotive force) appears on the high-voltage output terminals of the generator.

The waveform of a typical pulsed electromotive force (EMF) produced by the FEG is shown in Fig. 3.

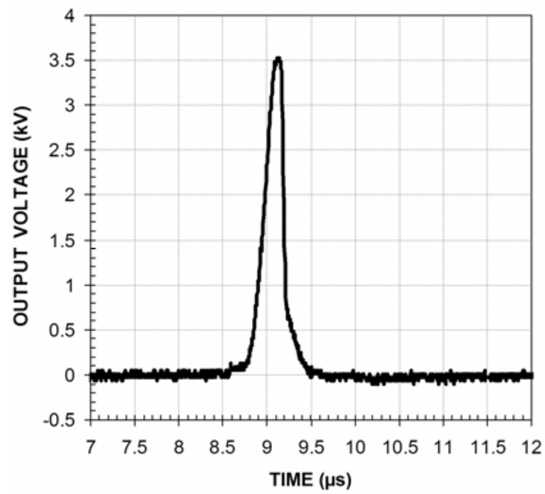

Figure 3. Waveform of the pulsed electromotive force produced by an FEG. Open circuit operation.

The EMF pulse amplitude reached $U_g(t)_{max}$ = 3.53 kV, the full width at half maximum (FWHM) was 0.21 μs, and the risetime was τ = 0.27 μs. The average EMF pulse amplitude in all five tests performed in this series of experiments was $U_g(t)_{max\ av} = 3.49 \pm 0.4$ kV.

In the charging mode the FEGs were used to charge capacitor banks of capacitances C_0 = 9, 18, and 36 nF. A schematic diagram of the system used to measure the operation of FEGs in the charging mode is shown in Fig. 4.

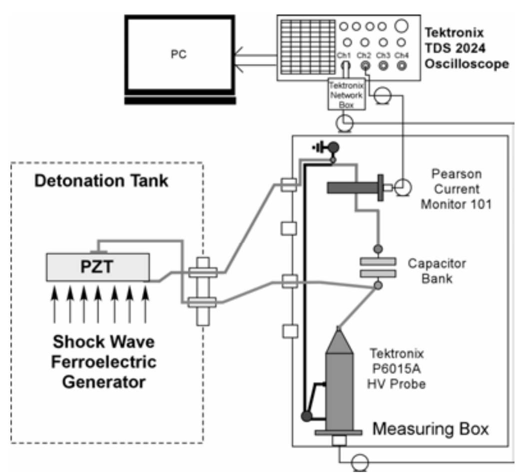

Figure 4. Schematic diagram of the measuring system used to investigate the operation of FEG in the charging mode.

The high-voltage output of the FEG was connected to the high-voltage terminal of the capacitor bank and to the

input of Tektronix P6015A high voltage probe. The negative front plate of PZT disk was connected to the ground terminal of the capacitor bank through the Pearson Current Monitor (Model 101).

Figure 5 shows a typical waveform of the high voltage produced by an FEG across a 9 nF capacitor bank.

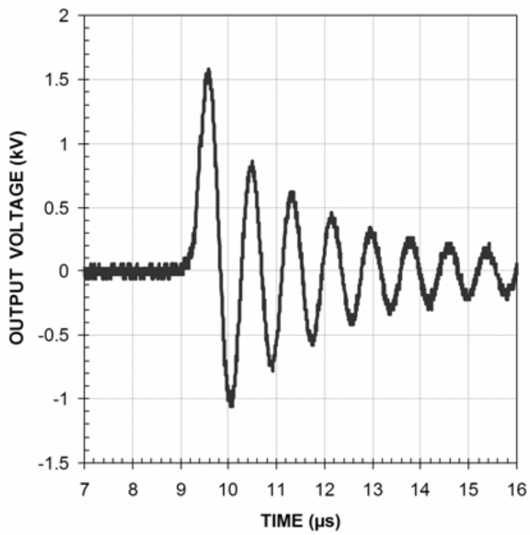

Figure 5. Waveform of a high voltage produced by an FEG connected to a 9 nF capacitor bank.

It is not a single pulse, but a series of oscillations. The frequency of oscillations is about 1.2 MHz. The peak voltage amplitude of the first pulse was $U(t)_{max}$ = 1.58 kV, the FWHM of the first pulse was 0.36 μs, and τ = 0.48 μs. The peak energy delivered to the capacitor bank (the first pulse in Fig. 5) reached $W = C_0\, U(t)_{max}^{2}/2$ = 11.2 mJ.

Figure 6 shows a typical waveform of the high voltage produced by an FEG across an 18 nF capacitor bank.

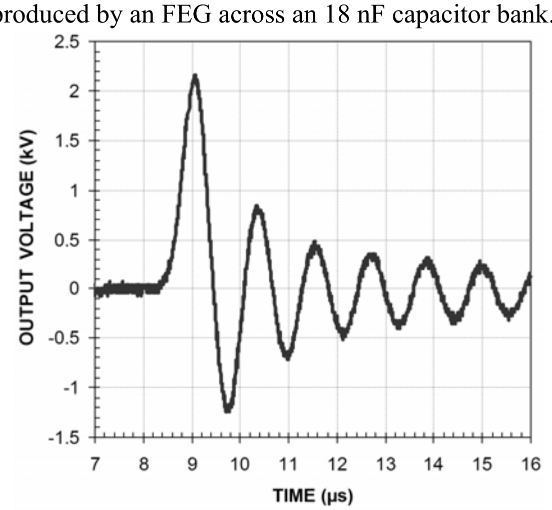

Figure 6. Waveform of a high voltage produced by an FEG connected to an 18 nF capacitor bank.

The output voltage oscillates as it did in the experiments with a 9 nF capacitor bank (Fig. 5). The frequency of oscillations is slightly lower, ~ 1.0 MHz. The peak voltage amplitude of the first pulse was $U\,(t)_{max}$ = 2.16 kV, the FWHM of the first pulse was 0.54 μs, and τ = 0.48 μs. The peak energy delivered to the capacitor bank (the first pulse in Fig. 6) reached W = 42 mJ.

The EMF pulse generated by the PZT module due to the shock wave depolarization causes a pulsed electric current, $I(t)$, to flow in the electrical circuit. Integration of the $I(t)$ waveform from 0 to t gives the momentary value of the electric charge, $\Delta Q(t)$, released to the electrical circuit during explosive operation of the FEG:

$$\Delta Q(t) = \int_0^t I(t)dt \qquad (1)$$

Figure 7 shows the waveform of the output current produced by the FEG in the load circuit (18 nF capacitor bank). The peak amplitude of the first current pulse was $I_1(t)_{max}$ = 140 A, the FWHM was 0.3 μs and τ = 0.52 μs. The peak amplitude of the second current pulse was higher than the first one and reached $I_2(t)_{max}$ = 180 A, with FWHM = 0.45 μs and τ = 0.31 μs.

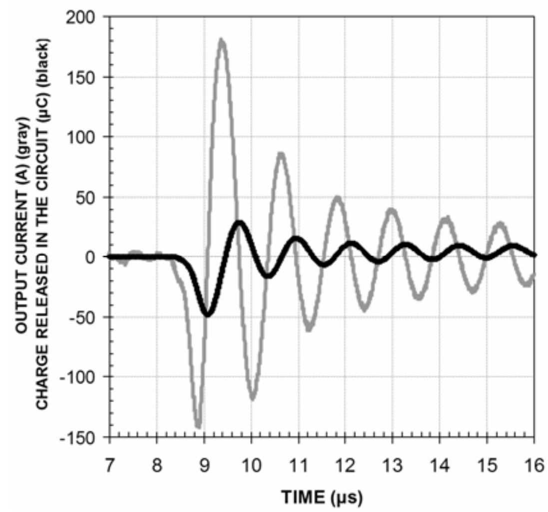

Figure 7. Waveforms of the output current (gray) and circulation of electric charge, $\Delta Q(t)$, (Eq. 2) (black) in the circuit of FEG loaded with an 18 nF capacitor bank.

The initial electric charge, Q_0, stored in the PZT energy-carrying elements can be determined as follows:

$$Q_0 = P_0 A \qquad (2)$$

where P_0 is the remnant polarization of the ferroelectric sample and A is its area. Accordingly, PZT disks with P_0 = 30 μC/cm^2 and A = 5.3 cm^2 have Q_0 = 159 μC.

As it follows from the experiment (Fig. 7), the electric charge transferred from a PZT module during explosive operation of the FEG to the capacitor bank, ΔQ_{max}, is about 30% of the initial charge stored in the ferroelectric element due to its remnant polarization, Q_0.

Figure 8 shows the waveforms of the output voltage, output current and output power for the experiment in which the load of the FEG was an 18 nF capacitor bank. The peak output power reached 0.24 MW.

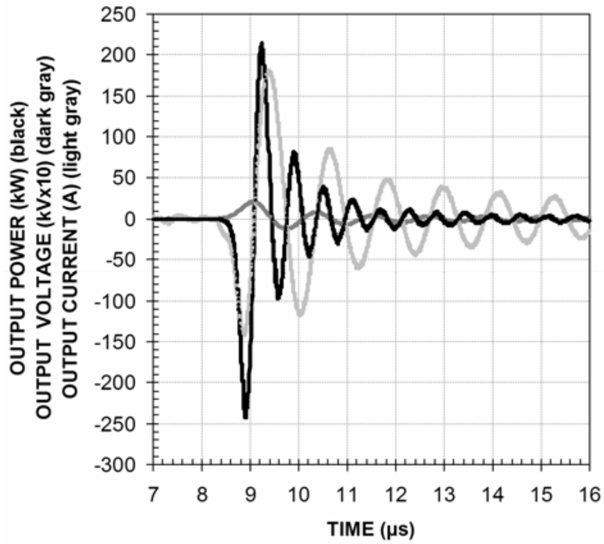

Figure 8. Waveforms of the high voltage (dark gray), current (gray) and power (black) produced by an FEG connected to an 18 nF capacitor bank.

Figure 9 shows a typical waveform of the high-voltage pulse produced by an FEG across a 36 nF capacitor bank. It is completely different from the results obtained for the 18 nF and 9 nF capacitor banks (Figs. 5 and 6). The FEG produced a single pulse with amplitude $U(t)_{max}$ = 1.82 kV (FWHM = 0.85 μs, τ = 0.93 μs) (Fig. 9). The energy delivered to the 36 nF capacitor bank was 60 mJ. The specific energy density of the PZT energy-carrying element in this experiment was 171 mJ/cm^3.

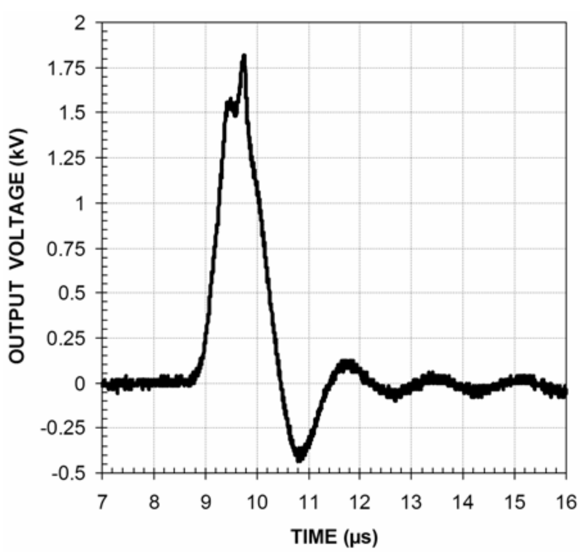

Figure 9. Waveform of the high voltage pulse produced by an FEG connected to a 36 nF capacitor bank.

The waveforms of the output voltage, output current and output power for this experiment are shown in Fig. 10.

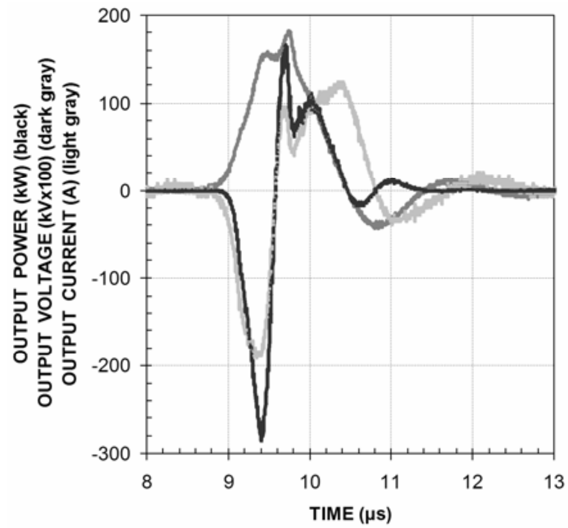

Figure 10. Waveforms of the output high voltage (dark gray), current (gray) and power (black) pulses produced by an FEG connected to a 36 nF capacitor bank.

The peak output power was 0.29 MW. The total charge delivered from the PZT energy-carrying element to the 36 nF capacitor bank in this experiment was ΔQ_{max} = 73 μC, which is 46% of the initial charge stored in the ferroelectric element due to its remnant polarization.

IV. SUMMARY

It has been demonstrated that it is fundamentally possible to pulse-charge a capacitor bank with a miniature explosive-driven high-voltage generator based on the longitudinal shock wave depolarization of poled $Pb(Zr_{52}Ti_{48})O_3$ piezoelectric ceramics. Charge transfer from the PZT energy-carrying element to the capacitor bank reached 46%. The specific energy density of the PZT module was 171 mJ/cm^3. The peak power in the load circuit reached 0.29 MW.

V. REFERENCES

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